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ELECTRICAL SIGNATURE ANALYSIS APPLICATIONS FOR NON-INTRUSIVE AUTOMOTIVE ALTERNATOR DIAGNOSTICS

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Abstract: Automotive alternators are designed to supply power for automobile engine ignition systems as well as charge the storage battery. This product is used in a large market where consumers are concerned with acoustic noise and vibration that comes from the unit, as well as overall quality and dependability. Alternators and generators in general are used in industries other than automotive, such as transportation and airline industries and in military applications. Their manufacturers are interested in pursuing state-of-the-art methods to achieve higher quality and reduced costs.

Preliminary investigations of non-intrusive diagnostic techniques utilizing the inherent voltage signals of alternators have been performed with promising results. These techniques are based on time and frequency domain analyses of specially conditioned signals taken from several alternators under various test conditions. This paper discusses investigations that show correlations of the alternator output voltage to airborne noise production. In addition, these signals provide insight into internal magnetic characteristics that relate to design and/or assembly problems.

Key Words: Alternator; analysis; diagnostics; electrical; generator; magnetic, signature

Summary: Electrical Signature Analysis (ESA) was developed originally at Oak Ridge National Laboratory to allow diagnostic related information to be gathered from electric motor driven devices via a remote non-intrusive current measurement on a motor power cable. The resulting signal with appropriate processing is sensitive to mechanical and electrical loads or anomalies occurring in the motor and driven machine or system. This technique has been developed for application on many different types of motors and driven machines. Recently the ESA technique has been extrapolated to evaluate alternators and generators and the perturbations seen in their voltage output signals.

The primary goal of this investigation is to determine if alternator electrical signals such as the phase

output voltage or rotor excitation voltage and current can be indicators of alternator acoustics problems believed to be related to the magnetic performance of the alternators. In addition we have used ESA to study the internal magnetic performance of the alternator in order to evaluate the manufacturing quality and operating condition of the unit.

Sound chamber testing is used for analysis of alternators to identify noise sources. These tests are complicated and time consuming to perform, and do not always produce consistent results due to the highly variable mounting configurations from vehicle to vehicle. Sound performance for a given alternator type has been known to vary considerably from vehicle to vehicle. Information that would quantify the root sources of alternator sound from an electrical or magnetic viewpoint would be very helpful and would remove the mounting configuration variables from the analysis process. This would enable design changes or field fixes to reduce sound.

Analyses in this study were conducted in several steps. The first and most obvious step was to perform a quick study of alternator acoustic behavior using the recorded sound data from two alternators. Based on these results, a comparison of various alternators' phase output voltage signals was initiated, using signal conditioning techniques on the phase output voltage. Other parameters such as rotor excitation current and rotor excitation voltage were also reviewed. Throughout the investigation, time domain and spectral analysis techniques were used, with the most interesting results arising in the time domain.

Test Setup Description: Data was collected on automotive alternators at a manufacturer's facility in the controlled environment of an alternator sound testing chamber. This chamber was designed to allow full control of alternator speed and load, with instrumentation for vibration and sound measurement. To this was added instrumentation required to collect electrical signatures from the various parts of the alternator. Vibration, sound, and electrical data were recorded for subsequent review and signal conditioning.

Data was collected using a test stand for mounting and running the alternators. The test stand supplied variable-speed belt-driven power to the alternator, a load for the alternator output, and computer control of speed, output current, and output voltage. Data was acquired from two microphones, an optical tachometer for alternator speed, an accelerometer, and electrical taps to read current and voltage from the test units. Test alternators were taken from a pool of units exhibiting sound and bearing problems. An alternator of "good quality", as designated by the manufacturer, was used for comparison purposes.

The following signals were collected using an 8 channel Digital Audio Tape (DAT) recorder:

Channel 1	optical tachometer pulse waveform
Channel 2	accelerometer mounted on the top of the alternator case (on the stator iron)
Channel 3	vertically mounted microphone
Channel 4	45 deg mounted microphone
Channel 5	output voltage, 3 phase, rectified, from alternator output terminals, divided by 12

Channel 6 output current using a current transformer (CT) clamped on power output wire *
Channel 7 regulator input current using CT probe **
Channel 8 Unrectified phase voltage (1 of 3 phase circuits, before rectifiers), divided by 100
* for some tests, this channel recorded rotor excitation voltage
** for some tests, this channel recorded rotor excitation current

The alternators used in these tests are designated as A17 (good unit), A16 (noisy unit), A6 (quietest style unit), A17R (A17 with induced rub), and A17S (A17 with slip ring damage). Data was collected for steady speed (2000 rpm & full load), speed ramp-up (1000-6000 rpm), and 20 amp and 40 amp controlled current at 2000 rpm.

Sound Analysis: Test results from A6 and A16 were compared for acoustic noise. A6 is a version of the A16 style, empirically found to be quieter by the manufacturer. PC based virtual instrument software programs were used extensively in this research along with some specially designed electronic signal conditioning circuits. A computer program was written to cascade (or waterfall) 30 acoustic spectra during ramp-up of the alternators. A cascade plot stacks sequential spectra of a given signal from bottom to top to provide a visual glimpse of changing frequency content during a period of time. Ramp-ups for these tests were started at 16 Hz rotational speed (RS) and monitored as the speed increased to ~100 Hz. The ramp data was used to determine which running speeds were the noisiest. Sound cascade plots of A6 and A16 are shown in Figure 1. A16 showed high sound production at 52 Hz RS. A6 was comparatively quiet with only a small peak at 43 Hz RS. Figure 1 demonstrates that 36xRS is the predominant component of sound for both units, but the sound cascades clearly show A16 to be noisier.

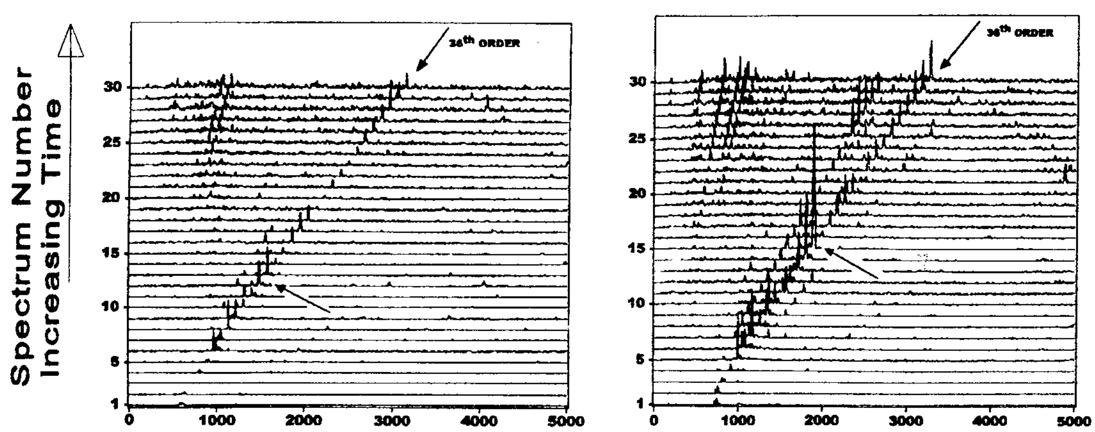

Figure 1 - Sound cascade plots during ramp tests for alternators A6 (left) and A16 (right)

An order tracking program was written to enable us to look at vibration and sound occurring at different multiples (orders) of running speed. This program tracks the speed of the alternator during ramp-up or coast-down using the optical tachometer output. A spectrum of data such as noise or vibration is acquired and sampled for a pre-determined order of rotational frequency. This

component of the frequency spectrum is plotted versus the RS for that sample. For the two alternators, 36xRS was examined in the vibration and the microphone signals to look for correlations when the noise was high, and to correlate sound behavior between the alternators. The readings taken using the order-tracking program showed the highest *vibration* for RS<40 Hz, while the alternator *sound* on all units peaked at 45-50 Hz (data not shown). This implies that the component creating the sound is not the component on which the vibration readings were taken (the external surface of the stator iron laminations). Figure 2 shows the magnitude of sound at the 36th order plotted against RS of A6 and A16. These order-tracked graphs of sound (Figure 2) correlate well with the cascade graphs (Figure 1) of sound, with order track frequency peaks matching the peaks seen in the cascade plots. The data above suggest that sound production is not necessarily related to speed, but possibly to mechanical resonances in the alternator case and supports. This is consistent with the observation that alternators sound different on different vehicles. All data analyzed showed

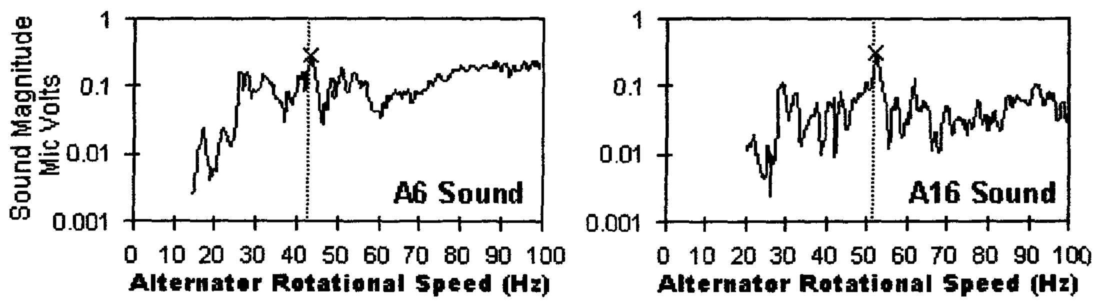

Figure 2 - Sound Magnitude tracked at the 36th order of turning speed for A6 and A16

that 36xRS was the sound driver, where 36xRS corresponds to the number of slots in the alternator stator (each rotor rotation "sees" 36 stator slots pass by).

Rotor and stator magnetic saturation conditions are believed to affect alternator transducing capability. To eliminate this possible interference, it was decided to look at lower alternator speeds

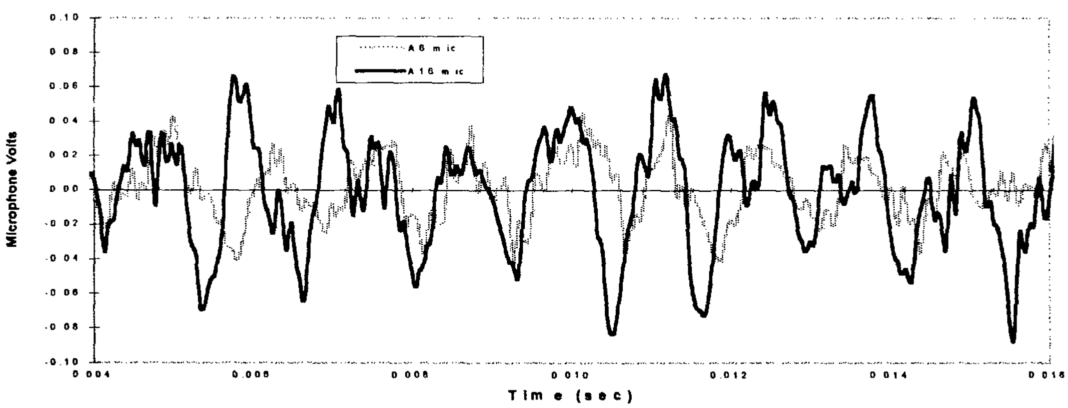

Figure 3 - Sound time waveforms from alternator A6 (gray) and A16 (bold) at 22 Hz

using the low end of the ramp data. Figure 3 shows raw time waveforms of the microphone signals taken from A6 and A16 with data acquired at 22 Hz RS. This speed was chosen because it was the lowest stable speed, and is well below magnetic saturation conditions in the iron. A6 (gray) shows lower sound amplitude than A16 (bold). The easily discernible main component in the wave is calculated to be at 36 x 22 Hz (786 Hz, 36th order). The 36th order is seen to be the sound driver here as well. This data demonstrates again that A16 is louder than A6, and is supported by data at other speeds.

Figure 4 shows voltage readings taken from the alternator's rectified outputs. This plot shows the first ESA-based evidence for differences between A16 and A6. It can be seen that the A6 voltage

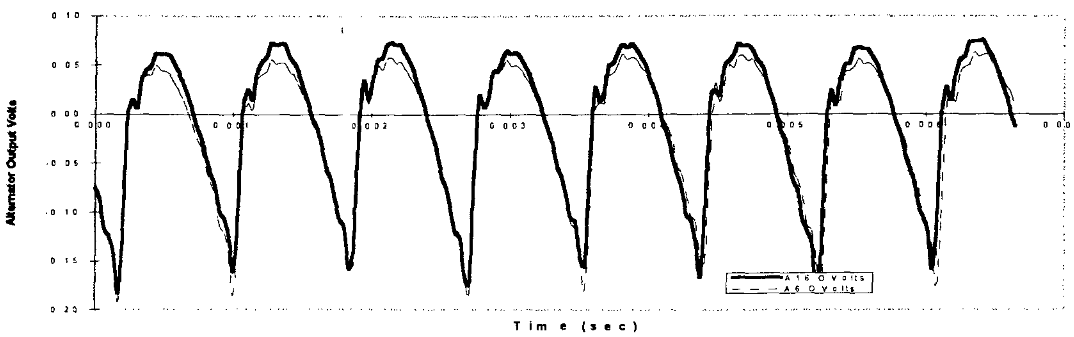

Figure 4 - Output Voltage Readings taken from A6 and A16

peaks are consistently lower than A16 voltage peaks. A similar analysis on the output current yields the same results (data not shown). The lower voltage and current may be related to lower internal magnetic force dynamics on the stator teeth and rotor poles.

Sound production is very likely related to magnetic "plucking" of these mechanical components inside the alternator, and some evidence of this is discussed later (see Pulse Ringdown). A6 has higher radial clearances between the rotor and stator teeth, and a large chamfer on the trailing edge of each rotor pole. This geometry affects the voltage and current output, suggesting the A6 unit is less efficient than units with tight geometry. The closer the radial clearance and the smaller the chamfer, the higher will be the rise rate in magnetic flux in a given stator tooth. This higher flux rise rate will result in a greater force in the stator tooth and greater mechanical deflection. A16 should experience higher dynamic forces due to it's tighter physical geometry. These forces will cause greater mechanical deflection in components such as stator teeth and rotor pole pieces, and thus more sound pressure generation.

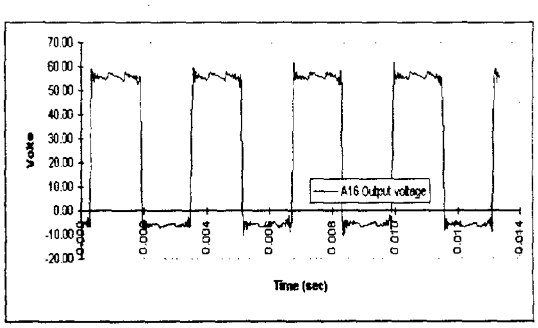

Figure 5 - Alternator Output Volts

Phase Voltage Analysis: The electrical signal

predominantly used for this study was the unrectified phase voltage (channel 8). This signal was acquired for all alternators and contains information related to stator and rotor magnetic behavior. In its unconditioned state the Phase Voltage (PV) consists of a square wave (Figure 5) having a peak-to-peak amplitude of about 60 volts. The frequency of this square wave is 6xRS generated from the 6-pole rotor passing the stator windings. Some broadband frequency content is carried on this wave, and is seen as ripples on the top and bottom of the PV wave. A circuit was developed to remove the large amplitude square wave component and amplify the other information in the signal, increasing the dynamic range of the "ripple" on the PV. This new signal is called the conditioned phase voltage (CPV, Figure 6), and was used to compare the alternators electrically. Two cycles of the CPV waveform are derived from one square wave of output voltage, the first cycle extracted from the top of the square wave and the second from the bottom.

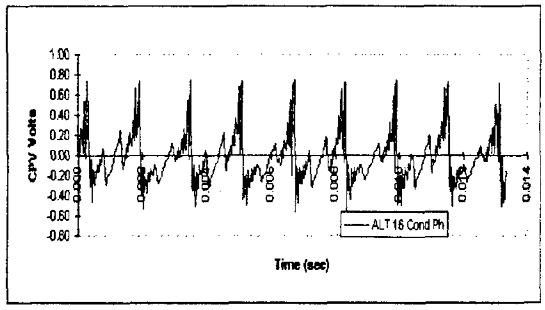

Figure 6 - Conditioned phase voltage

Figure 7 compares the CPV for four alternators examined in this study. The CPV waveforms of the alternators are very similar, to the extent that it was initially questioned whether the signal would contain any valuable alternator diagnostics. It is seen with the implanted rub and slip ring defects that the CPV clearly demonstrates diagnostic capability. All these units are running at a 2000 rpm steady state full load condition. It can be seen that nearly every deviation in the wave is matched by all four alternators. The running conditions for these tests are such that the iron in the rotor and stator are probably magnetically saturated creating a stabilizing but filtered effect.

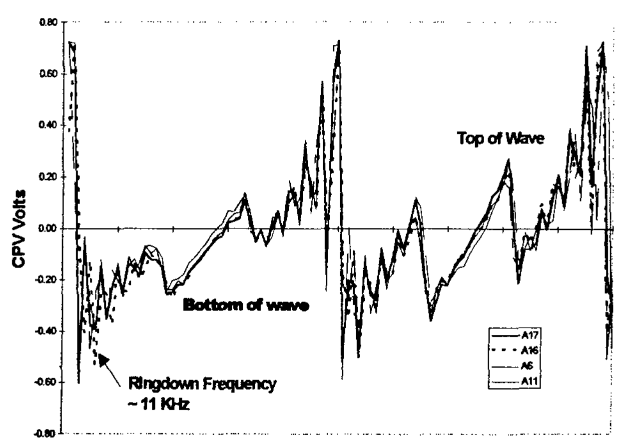

Figure 7 - Comparison of Alternator CPV

Rub and Slip Ring Damage Evaluation: Defect conditions were evaluated by using specially prepared hybrid parts along with A17. By distorting the stator a "rub" defect was implanted and is designated A17R. A "dent" placed on the slip ring produced the defect designated as A17S. These data analyses proved to be educational and indicate valuable diagnostic potential in these signals.

Figure 8 shows two time waveforms of sound (top) and CPV (bottom) for A17R. The sound wave shows pulses at running speed (52 Hz), which are the result of the rotor/stator rub. In the CPV wave

the arrow tails indicate disturbances in the amplitude that closely correlate to sound wave pulses (at arrow head). The CPV amplitude drops and there is a subsequent sound pulse at an estimated time lag of 10-13 milliseconds. Through several similar tests, the time lag was determined to be the same.

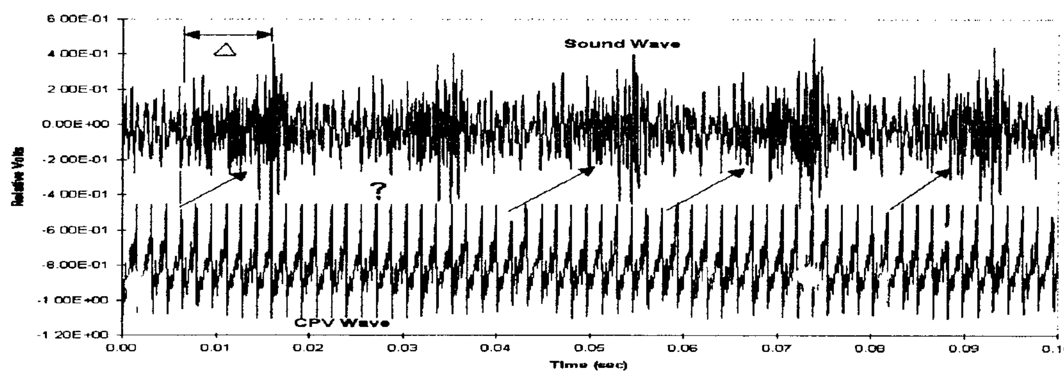

Figure 8 - CPV anomalies corresponding to sound pulses

The dented slip ring data shows interesting results and produced many areas of potential study on the nature of the alternators and the signals they produce. The pulse caused by the slip ring dent served as a "signal generator" that helped evaluate several aspects of the alternator behavior. Figure 9 shows a plot of sound and high pass filtered rotor excitation current (REC) for A17S. There is an obvious correlation between the sound wave and the REC signal showing brush "clicks" as the brush passes over the dent in the slip ring. The REC is supplied through the slip rings and should be fairly sensitive to slip ring related defects. This particular test was performed at 52 Hz RS. The sound pulses correlate to a once-per-rotation frequency, as do the REC pulses. The 3rd and 5th REC pulses shown in Figure 9 are undersized and are believed to be due to brush float after striking the dent in the slip ring. Rotor excitation voltage data (not shown) also supports the brush floating theory. A transient is also visible in the CPV data (not shown) as well when the REC spikes are large, while no CPV transient is observed when the REC pulses are small (as for the 3rd and 5th pulses).

Figure 9 also shows a time lag from the electrical REC pulse to the sound pulse received at the microphone. This time is estimated at 12 milliseconds, approximately equal to the time lag mentioned previously in

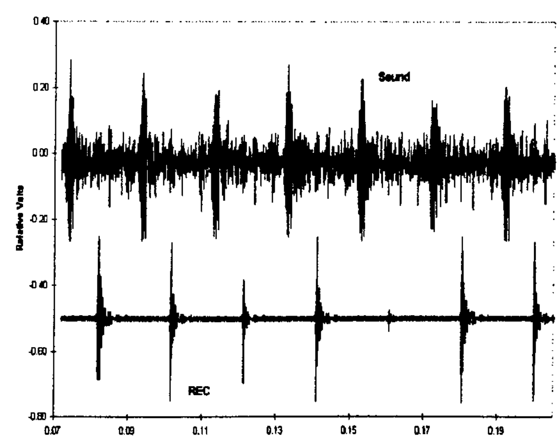

Figure 9 - Correlation of REC to Sound Pulses

the rub discussion. There is acoustic time lag due to sound travel from the alternator to the microphone (2 feet in air), but this equals ~1.5 milliseconds, leaving 10.5 milliseconds of time unaccounted for. The plot in Figure 10 compares sound, *vibration* and CPV. The calculated acoustic time lag (1.5 ms) correlates well with this plot; the vibration pulse of the stator outer surface (accelerometer location) occurs 1.5 ms before the microphone signal shows it. Looking back in time in the CPV we find the characteristic pulse caused by the brush click at 10 - 11 ms before the vibration pulse. This implies that there is a 10.5 ms lag *inside the alternator*, possibly related to mechanical impedance or inductance effects. At this particular speed the lag is equal to about 50% of one rotor rotation. This significant amount of time lag is indicative of sound propagation behavior inside the alternator. In the case of the 36xRS driven sound, the time lag may be due to vibration traveling down into the rotor from a vibrating rotor pole (magnetically excited at 36xRS), through the shaft and bearings, and *then* into the alternator case (and accelerometer) where it acoustically couples to the air.

It has been observed that, given two similar alternators, one may be noisy and the other relatively quiet. Our data suggests that it is possible that *good manufacturing tolerances* in stator slot or rotor pole spacing and magnetic symmetry could cause increased sound production. Excellent symmetry (i.e. good manufacturing tolerances) could cause several poles to be "plucked" *in-phase* creating higher sound pressure.

Pulse Ringdown in the CPV: Each cycle of the CPV shows three periodic events (see Fig 5 & 7) having the appearance of ringdowns with an event period of 36xRS. The subsequent ringing could be related to inductive resonance effects, or to mechanical effects of components moving inside the alternator. The ringdown frequency seen in the time domain data (Fig 7) is estimated at 11 kHz.

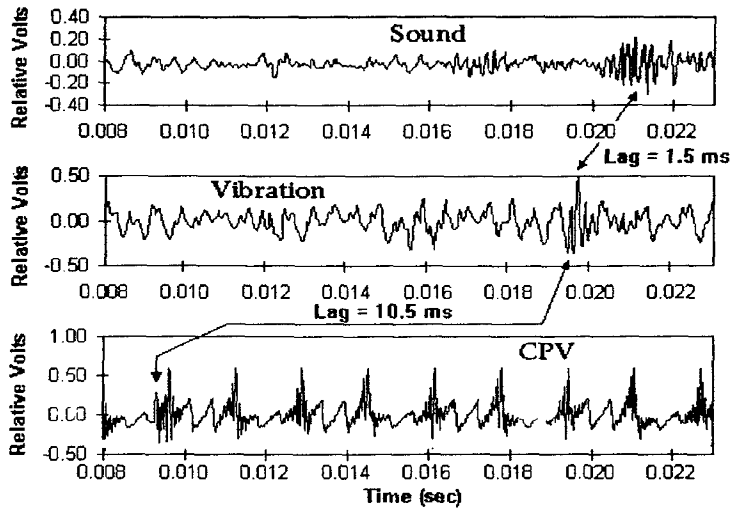

Figure 10 - Sound and vibration pulse comparison

In keeping with the theory mentioned in the rub and slip ring section about rotor pole vibration, a cursory impact test on one of the rotor poles on the sample alternator brought back from the manufacturer was performed. The impact was performed at the tip of the pole with the accelerometer located near the base to reduce the accelerometer mass loading effect on the pole's natural frequency. The test configuration is shown in Figure 11A and the spectral results are shown in Figure 11B. The primary peak seen in this impact test (10.6 kHz) is very close to the 11 kHz ringdown estimate (above) and suggests a relationship to the waveform ripple seen in Figure 7.

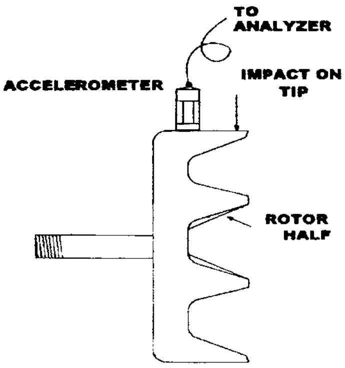

Figure 11A - Rotor Impact Sketch

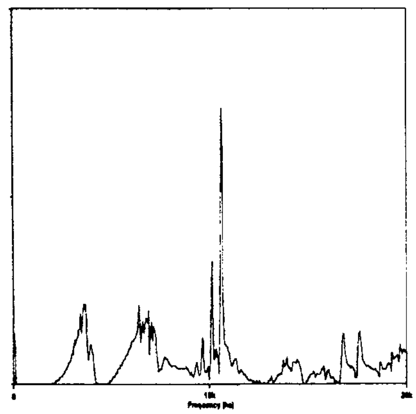

Figure 11B - Impact response Spectrum

Output Volts Analysis: Figure 12 shows two waves which are taken from the same continuous output voltage waveform. The solid wave has 36 stator tooth passing pulses representing one rotation of the alternator. The dashed data is the next consecutive rotation of the alternator, showing the similarity of the magnetic performance of the rotor/stator from one rotation to the next (the dashed data is a sequential group of 36 pulses superimposed on the previous 36 pulses and shifted ½ cycle to the right for clarity). The shape and magnitude of each peak is directly comparable, and shows stator magnetic "shape" or magnetic "trueness" within one rotation of the rotor. This analysis allows one to evaluate winding insulation degradation on a slot-by-slot basis, a weak stator section, machining quality, rotor eccentricity, winding inductive balance, and other degradation phenomena. As-assembled "magnetic" condition can also be evaluated with this method.

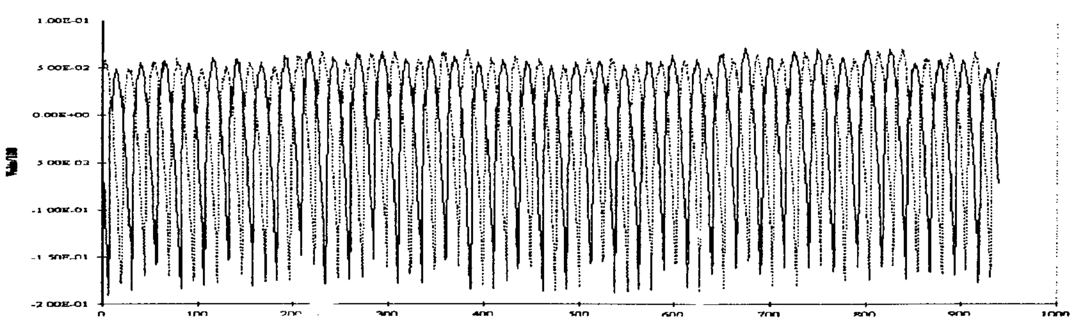

Figure 12 - A6 Output volts, Overlay of Two Full Rotations

Since alternators are mainly electrical in nature, ESA techniques provide good insight into the internal performance. Figure 13 demonstrates the ability of ESA to "look" inside the alternator, showing a plot of output voltage, with the data taken at 22 Hz RS. A6 shows a "softer" more rounded off peak than the other alternators. Particularly A16 shows a very sharp, square wave shape; the other alternator shown exhibits a similar sharp shape, especially in the leading edge. This is a good indicator of the magnetic flux "wave shape" and is related to sound production in the alternator.

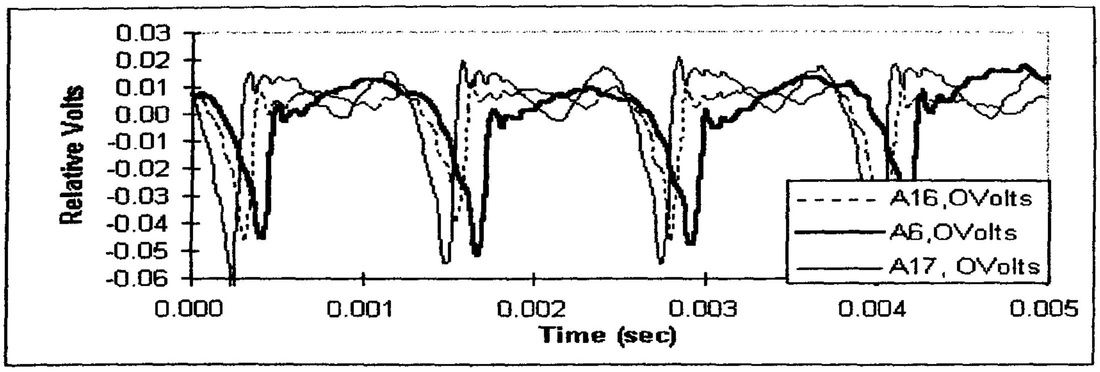

Figure 13 - Alternator wave shape comparison

Conclusions: Microphone sound data was reviewed and indicated A16 to be the noisier unit. It was found that sound correlates well with the output volts wave shape, and this could lead to design aids that would improve alternator noise levels.

Variability between units of similar design has been a source of problems to the testing efforts of manufacturers. Data seen here agrees that indeed this is a problem, and this study proposes ways to avoid the difficulties encountered with conventional methods. Electrical signature analysis is inherently less sensitive to mechanical resonances and external vibrations and more sensitive to the electrical drivers inside the alternator.

ESA was shown to be highly sensitive to rotor-to-stator rub and the slip ring defect, and reveals much about the magnetic processes inside the alternator. Future work will lead to a better understanding of the magnetic and mechanical interaction of stator slots and rotor poles.

A fundamental understanding of the sound source will lead to improved design and manufacturing efforts and ESA provides a non-intrusive view into the alternator's behavior. The output voltage wave analysis shows the magnetic shape or trueness stemming from the manufacturing process.

The impact and time lag analyses suggest that the predominant sound at 36xRS is generated by vibration of the rotor poles. Further study is indicated to determine the precise sound source, with the ultimate goal being to improve the design or manufacturing process to reduce noise at the source.

This study opens the door to analysis of many aspects of alternators, and would be easily extrapolated to generators and similar devices such as electric clutches and brakes. Significant impact can be realized in the area of manufacturing quality, as well diagnostics and prognostics of operating units and units in repair shops.